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Acoustical evaluation of carbonized and activated cotton nonwovens

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ABSTRACT

An activated carbon fiber nonwoven (ACF) was manufactured from a cotton nonwoven fabric. For the ACF acoustic application, a nonwoven composite of ACF with cotton nonwoven as a base layer was developed. Also produced were the composites of the cotton nonwoven base layer with a layer of glassfiber nonwoven, and the cotton nonwoven base layer with a layer of cotton fiber nonwoven. Their noise absorption coefficients and sound transmission loss were measured using the Brüel and Kjær impedance tube instrument. Statistical significance of the differences between the composites was tested using the method of Duncan's grouping. The study concluded that the ACF composite exhibited a greater ability to absorb normal incidence sound waves than the composites with either glassfiber or cotton fiber. The analysis of sound transmission loss revealed that the three composites still obeyed the mass law of transmission loss. The composite with the surface layer of cotton fiber nonwoven possessed a higher fabric density and therefore showed a better sound insulation than the composites with glassfiber and ACF.

1. Introduction

Activated carbon materials are ideal for use as high-performance adsorbents and absorbents, because of their very high specific surface area up to 2500 m^2/g and a high micropore volume up to 1.6 ml/g (Suzuki, 1994). Activated carbon materials are made from carbonaceous materials by carbonization and activation. Carbonization is a thermochemical process (pyrolysis) which converts carbonaceous materials into active carbon products. Carbonaceous materials can be either natural organic substances, such as wood, coconut, shells, and bagasse, or synthetic resins or polymers like saran, polyvinylidene chloride, etc.

Granulated charcoal has been a major type of activated carbon for many years, because of abundance and low cost of the raw material wood. However, the granulated form of charcoal is usually difficult to handle in many industrial processes, and therefore is limited to many advanced applications. With a purpose of seeking flame-resistant textiles, the methods of producing activated carbon fibers (ACF) by carbonizing and activating cellulosic fibers have been reported since the 1960s (Bacon and Tang, 1964; Tang and Bacon, 1964). Compared to activated carbon granules or powder, ACF has a significantly different microporous structure (Carrott, 1991; Ehrburger et al., 1992; Starek et al., 1994). Previous research has reported that the ACF product has the advantages of product quality consistency and much faster dynamic adsorption characteristics that allow less weight to be used for a given application than granulated or powdery form (Brown et al., 1987).

Current major fiber precursors for producing commercial ACF fabrics include rayon, acrylic, polyacrylonitrile (PAN), and Novoloid (novolac resin). In the past few decades, the raw material for activated carbon fiber is especially focused on viscose rayon, a regenerated cellulosic fiber commonly used in the nonwovens industry. Rayon manufactures uses large amounts of water and energy and an additional environmental concern is the emission of zinc and hydrogen sulfide. After 1985, the production of rayon decreased dramatically in the US and EU countries. This paper focuses on carbonizing and activating a cotton nonwoven fabric. Cotton is the most popular fiber crop produced in the US. Cotton fiber also has a hollow structure that helps increase surface area and porosity. Thus, a specialty cotton nonwoven with high performance in chemical absorption and adsorption could be obtained.

Reported end uses of the activated carbon fiber fabrics cover many industrial sectors with main application focuses on personal safety equipment (protective clothing and masks), solvent recovery, water/air purification, wastewater treatment, and heat and electric insulation (Freeman et al., 1987, 1988, 1989; Freeman and Gimblett, 1987, 1988; Huang et al., 2002). However, there is a lack of reports on activated carbon fiber materials for acoustical applications. Textile fabrics, particularly nonwoven fabrics, have been commonly used for sound absorption, because of a special structure formed by fiber or yarn in fabrics (Kosuge et al., 2005; Lou et al., 2005; Shoshani and Yakubov, 1999, 2000; Shoshani, 1990; Shoshani and Wilding, 1991). In general, dry porous media saturated with air were capable of reducing the level of ambient

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noise. Sound transmission loss is the reduction in noise level resulting from passage through an obstruction. The best way to reduce sound transmission is to use construction techniques that dampen vibration and convert sound energy into heat of friction. Activated carbon fiber fabrics have two levels of porous structures: macropores among fibers and yarns; and micropores on the surface of activated carbon fiber. This unique fabric architecture renders a great potential for the activated carbon fiber fabrics to be used as high-performance and cost-effective acoustical materials.

A major purpose of this study is to manufacture carbonized and activated cotton nonwoven and explore its potential as a biodegradable acoustic material for specialty industrial applications. Moreover, cotton based activated carbon fabrics tend to have weak mechanical properties after carbonization and activation at high temperatures. This may limit some prospective end uses for the activated carbon fabrics. The tensile strength of the cotton nonwoven and the carbonized and activated cotton nonwoven is evaluated.

2. Experiment

2.1. Sample preparation

Carbonization of the cotton nonwoven was carried out in an oven with nitrogen atmosphere at 350 °C and a heating rate of 20 °C/min. The cotton nonwoven was held in the oven for 20 min to obtain around 75% weight loss. The CO_2 activation of the carbonized cotton nonwoven was undertaken at the temperature of 350 °C for 20 min to form activated cotton with a total weight loss of 80%.

The experimental acoustical nonwoven was designed with a composite structure. This nonwoven composite has two layers: a base layer and a surface layer (Fig. 1). The base layer nonwoven was raw cotton nonwoven (unbleached). Three different nonwoven products were employed as the surface layer, respectively. These surface layer nonwovens were bleached cotton nonwoven, ACF cotton nonwoven, and glassfiber nonwoven. The glassfiber web was produced by Johns Manville (Denver, CO, USA). The specifications of the materials used for this study are listed in Table 1.

2.2. Tensile test

To examine the strength reduction of the cotton nonwoven after carbonization and activation, tensile strength of the surface cotton nonwoven and ACF cotton nonwoven was measured using an Instron tester in both along- and cross-machine directions in accordance with ASTM D 5035. The sample gauge length was 7.5 cm and the sample width was 2.5 cm.

2.3. Measurement of sound absorption

The measurement of sound absorption of the nonwovens was based on the method of ASTM E 1050: Standard Test Method for Impedance and Absorption of Acoustical Properties Using a Tube, Two Microphones and a Digital Frequency Analysis System. This method was developed to determine the ability of materials for absorbing normal incidence sound waves. A Brüel and Kjær measuring instrument was used for testing within the frequency range 0–6.4 kHz. This instrument includes Type 4206 Impedance Tube, PULSE Analyzer Type 3560, and Type 7758 Material Test Software. The testing principle of this system is illustrated in Fig. 2. A sound source is mounted at one end of the impedance tube and the material sample is placed at the other end. The loudspeaker generates broadband, stationary random sound waves. These incident sound signals propagate as plane waves in the tube and hit the sample surface. The reflected wave signals are picked up and compared to the incident sound wave. The frequency range to be tested depends on the diameter of the tube. A large tube (100 mm diameter) is set up for measuring the nonwoven sound absorption in the low frequency range from 50 Hz to 1600 Hz. A small tube (29 mm diameter) is set up for testing the material sound absorption in the high frequency range of 500–6400 Hz. Three specimens were tested for each type of the experimental acoustic nonwoven composites.

Table 1
Fiber and nonwoven specifications.

Nonwoven	Weight (g/m^2)	Thickness (mm)
Cotton base	62	35
Cotton surface	274	3
ACF cotton surface	89	3
Glassfiber surface	127	3

2.4. Measurement of sound insulation

Sound transmission loss (TL) represents the loss in sound power during sound transmission through a specimen. The higher the transmission loss, the less the sound waves pass through the specimen. The TL tests are divided into two parts. In the first stage no sample is placed between the impedance tubes. In this case, the results should be 100% transmission and 0% reflection. In the second stage the sample is put between the noise source tube and receiving tube. The incident noise waves hit the sample and are divided into three parts: reflected waves, absorbed waves, and transmitted waves (Fig. 3). By measuring the sound pressure at the four microphone locations 1, 2, 3, and 4, transmission loss of the material can be determined. The Brüel and Kjær instrument with Type 4206T Impedance Tube (Fig. 3) for testing normal incidence sound transmission loss is used for this evaluation. The instrumental set up includes four microphones and two tubes discussed above (large tube for measuring sound frequencies within 100–1600 Hz; small tube for measuring sound frequencies within 1600–6400 Hz).

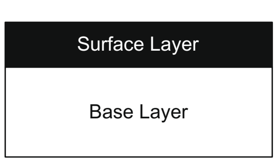

Fig. 1. Acoustical nonwoven structure.

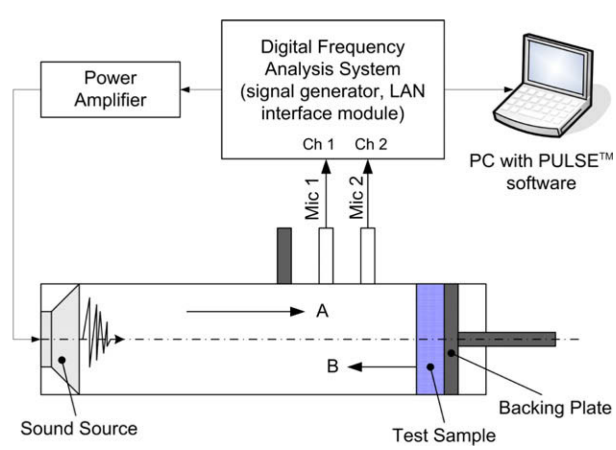

Fig. 2. Measuring system configuration.

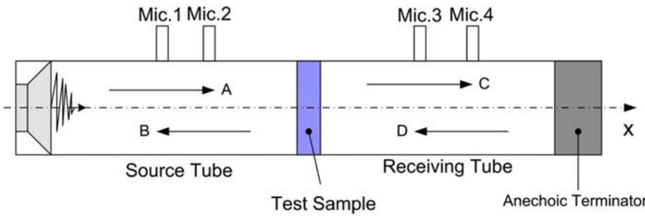

Fig. 3. Sound transmission loss measurement system.

3. Results and discussion

3.1. Fabric tensile strength

The data listed in Table 2 are average tensile strength. After the carbonization and activation, the breaking strength of the cotton nonwoven decreased from 16.6 N to 1.3 N in along-machine direction and from 33 N to 1.4 N in cross-machine direction. This may result from pyrolytic degradation during carbonization. High temperature causes the C–O and C–C bonds to split in cellulose, and as a result, tars, water, carbon monoxide, and carbon dioxide are produced. Despite a significantly reduced tensile strength due to the carbonization, the ACF cotton nonwoven maintained a good web form.

3.2. Sound absorption

The normal incidence sound absorption coefficients (α) of the cotton composites are determined as a function of the sound frequency (f), as shown in Fig. 4. The plotted curves combine the measured data in the low frequency range of 100–1600 Hz (using the Type 4206 large tube) and the measured data in the high frequency range (500–6400 Hz tested by the Type 4206 small tube) together to indicate a whole bandwidth of the 1/3 octave band frequency. The x-axis uses a log scale. By examining the curve, it can be seen that Base and ACF cotton exhibits the highest ability for normal incident sound absorption, superior to Base and Glassfiber and Base and Cotton. Mostly because of a hollow structure of cotton fiber, the cotton nonwoven as surface layer absorbs more sound waves than the glassfiber nonwoven that is widely used as noise absorbent materials. The reason why the ACF cotton nonwoven possesses a significantly higher sound absorption coefficient than raw cotton may be explained by the highly porous surface structure of the ACF cotton nonwoven. More porous areas mean more air volumes allowed to flow into the ACF nonwoven structure. When incident noise waves hit the nonwoven composite, air vibration would happen in both the macroporous and microporous areas. As a result, the incident waves can be absorbed considerably.

For a numerical comparison, the average values of the sound absorption coefficients for all the nonwovens were calculated using the following equation:

$$\bar{\alpha} = \frac{\int_{F_1}^{F_2} \alpha(f)df}{F_2 - F_1}, \quad (1)$$

where F_1 is lower bound of sound frequency in testing and F_2 is upper bound of sound frequency in measurement. The computed

Table 2
Tensile strength of nonwoven fabrics.

Nonwoven type	Break strength (N)		Elongation at break (%)	
	Along-machine	Cross-machine	Along-machine	Cross-machine
Cotton	16.6	33.0	45	48
ACF cotton	1.3	1.4	10	23

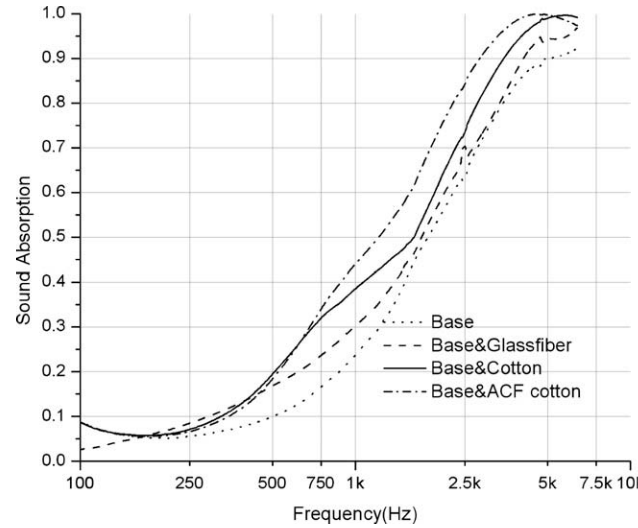

Fig. 4. Absorption coefficients of nonwovens.

$\bar{\alpha}$ values between F_1 (100 Hz) and F_2 (6400 Hz) for the acoustic nonwovens are listed in Table 3.

It can be observed that all the $\bar{\alpha}$ values for the three base layer nonwovens were within the range of 0.65–0.80. The $\bar{\alpha}$ values of four nonwoven composites are grouped into four different groups as tested by the Duncan's grouping at the 0.05 significance level (Table 3). The ACF cotton nonwoven used as surface layer is significantly better than glassfiber and bleached cotton nonwovens. This indicates that the cotton nonwovens could be used as a biobased acoustic material with an outstanding ability to absorb normal incidence noise and a substantially lighter weight compared to the glassfiber nonwoven. It also reveals that the process of carbonization and activation for the cotton nonwoven improves sound absorption significantly. From Table 1, it can be seen that the ACF cotton surface layer features the light nonwoven structure. Its combination with the base layer forms the lightest composite structure. Therefore, in the present case the Base and ACF cotton composite seems an optimal acoustic material for the application of noise absorption.

3.3. Transmission loss

Fig. 5 shows the curves for transmission loss (TL) as a function of the sound frequency (f) within the frequency range of 100–6400 Hz with log scale as x-axis. The curves indicate that the three surfaces of glassfiber, cotton nonwoven, and ACF cotton all improve the nonwoven performance of sound insulation. It seems that the cotton nonwoven and ACF cotton nonwoven show better transmission loss than glassfiber during the low frequency range from 350 to 1600 Hz. All three types of surface show no difference during the high frequency range from 1600 to 6400 Hz.

Similar to the sound absorption, the average values of the transmission loss for all the nonwovens were defined by the following equation:

$$\overline{TL} = \frac{\int_{F_1}^{F_2} TL(f)df}{F_2 - F_1}, \quad (2)$$

where F_1 is lower bound of sound frequency in testing and F_2 is upper bound of sound frequency in measurement. The $\overline{TL}$ values between F_1 (100 Hz) and F_2 (6400 Hz) for the acoustic nonwovens are listed in Table 4.

The $\overline{TL}$ values for Base and Glassfiber, Base and Cotton and Base and ACF cotton are grouped into one group (B) by the statistical

Table 3
Means of sound absorption coefficient ($\bar{\alpha}$).*

	Base	Base and glassfiber	Base and cotton	Base and ACF cotton
1	0.649	0.683	0.733	0.799
2	0.650	0.684	0.749	0.792
3	0.656	0.701	0.750	0.795
Mean	0.652 (A)	0.689 (B)	0.744 (C)	0.795 (D)

* Means with the same letter are not significantly different at the 95% confidence level.

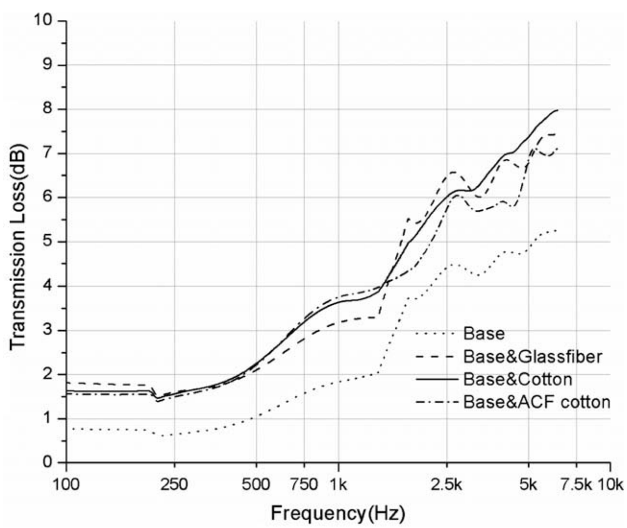

Fig. 5. Transmission loss of nonwovens.

Table 4
Means of transmission loss ($\overline{TL}$).*

	Base	Base and glassfiber	Base and cotton	Base and ACF cotton
1	3.170	4.170	6.031	5.224
2	3.315	6.611	5.685	5.630
3	4.144	6.229	5.859	5.354
Mean	3.543 (A)	5.670 (B)	5.858 (B)	5.436 (B)

* Means with the same letter are not significantly different at the 95% confidence level.

test of the Duncan's multiple-range comparison, meaning no significant difference at the 95% confidence level. The reason why the surface layer cotton nonwoven shows slightly better sound insulation than the glassfiber and ACF cotton nonwovens is that sound TL mostly depends on the mass law. The sound TL mass law states that TL increases as the mass increases. As exhibited in Table 1, the cotton surface shows the highest average TL value because it has the highest mass per unit area (274 g/m^2) of the three surface layers.

4. Conclusions

A carbonized and activated cotton nonwoven was produced and the experimental acoustical nonwovens were designed with a composite structure. The cotton nonwoven composites with three surface layers (glassfiber, cotton and ACF cotton) were evaluated in terms of their acoustic properties for sound absorption and sound insulation. The Brüel and Kjær impedance tube instrument was used for measuring the normal incidence sound absorption coefficient and transmission loss of the experimental composites. The comparison of the sound properties was carried out using the statistical method of variance analysis. The results showed that the nonwoven composites with cotton as a surface layer had significantly higher sound absorption coefficients than the glassfiber-surfaced composite in the frequency range from 100 to 6400 Hz. Meanwhile, carbonization and activation of the cotton nonwoven improved sound absorption ability significantly. For the sound transmission loss, there was no significant difference among the three surface layers. Considering the lightweight, biodegradability and low cost of the cotton raw material, the carbonized and activated cotton nonwoven has a potential to be used as high-performance and cost-effective acoustical materials.

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